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Evaluation of MODIS NPP and GPP products across multiple biomes

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Abstract

Estimates of daily gross primary production (GPP) and annual net primary production (NPP) at the 1 km spatial resolution are now produced operationally for the global terrestrial surface using imagery from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor. Ecosystem-level measurements of GPP at eddy covariance flux towers and plot-level measurements of NPP over the surrounding landscape offer opportunities for validating the MODIS NPP and GPP products, but these flux measurements must be scaled over areas on the order of 25 km^2 to make effective comparisons to the MODIS products. Here, we report results for such comparisons at 9 sites varying widely in biome type and land use. The sites included arctic tundra, boreal forest, temperate hardwood forest, temperate conifer forest, tropical rain forest, tallgrass prairie, desert grassland, and cropland. The ground-based NPP and GPP surfaces were generated by application of the Biome-BGC carbon cycle process model in a spatially-distributed mode. Model inputs of land cover and leaf area index were derived from Landsat data. The MODIS NPP and GPP products showed no overall bias. They tended to be overestimates at low productivity sites — often because of artificially high values of MODIS FPAR (fraction of photosynthetically active radiation absorbed by the canopy), a critical input to the MODIS GPP algorithm. In contrast, the MODIS products tended to be underestimates in high productivity sites — often a function of relatively low values for vegetation light use efficiency in the MODIS GPP algorithm. A global network of sites where both NPP and GPP are measured and scaled over the local landscape is needed to more comprehensively validate the MODIS NPP and GPP products and to potentially calibrate the MODIS NPP/GPP algorithm parameters.

Keywords: MODIS; Landsat; Net primary production; Gross primary production; Biomes; Validation; Global; Monitoring

1. Introduction

A standard suite of global products characterizing vegetation cover, leaf area index, gross primary production (GPP), and net primary production (NPP) at the 1 km spatial resolution is now being produced operationally based on observations from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor (Justice et al., 2002; Running et al., 2004). The GPP product has an 8-day temporal resolution and is intended for monitoring seasonal and spatial patterns in photosynthetic activity. MODIS NPP is an annual value and provides a means of evaluating spatial patterns in productivity as well as interannual variation and long term trends in biosphere behavior (e.g. driven by climate variation or change, Nemani et al., 2003). Validation of these products is an essential step in establishing their utility; however, validation is challenging because of a variety of scaling issues (Morisette et al., 2002; Turner et al., 2004). These issues include matching the 1-km resolution of the MODIS products with plot-scale measurements on the ground

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(Cohen et al., 2003a; Turner et al., 2003a, 2004, 2005). The BigFoot Project (2005) was designed to address many of these scaling issues, and here we report on comparisons of BigFoot and MODIS-based GPP and NPP at 9 sites representing a range of biome types.

Validation of the MODIS GPP product has generally taken the form of time series comparisons between GPP estimated from eddy covariance flux tower data and GPP from MODIS for one or more 1-km^2 cells surrounding the tower (Heinsch et al., in press; Turner et al., 2003a, 2005; Xiao et al., 2004). These studies have found a wide range of site-specific agreement or disagreement between the ground-based and MODIS-based GPP estimates. Specific causes of over- or underprediction of GPP in the MODIS product have been traced to MODIS GPP algorithm inputs, including the climate input data, the FPAR (fraction of incoming photosynthetically active radiation that is absorbed by the canopy), and the base rate for light use efficiency. Site-level validation of MODIS NPP has been more limited because of the logistical constraints of measuring NPP and scaling it to the size of a MODIS grid cell (Turner et al., 2004, 2005). These efforts have likewise found site-specific differences in the degree of agreement between ground-based and MODIS-based NPP estimates. The MODIS NPP algorithm requires the computation of autotrophic respiration (R_a) based on inputs of leaf area index (LAI) and temperature, along with look-up table values for allometric constants and the base rate of respiration (Running et al. 2000). Specific problems with the R_a component of NPP have been identified in some cases (Turner et al., 2005).

This paper will present NPP/GPP validation results from the complete set of BigFoot sites. Biome types include boreal forest, temperate coniferous forest, temperate hardwood forest, and tropical moist forest, as well as arctic tundra, temperate grassland, desert grassland, and agricultural fields. A virtue of the BigFoot approach is that a common NPP/GPP scaling protocol based on Landsat data was employed across these widely divergent sites, thus increasing the possibilities for analysis of cross-site patterns. One value of taking a synoptic view of MODIS product performance is that it may reveal possible biases that could be addressed in future releases of the MODIS products or in the design of planned follow-up projects associated with Earth System monitoring.

2. Methods

2.1. Overview

At each of the nine BigFoot sites, digital maps (25 km^2) of land cover, LAI, daily GPP, and annual NPP were developed for one or more years using a combination of imagery from the Landsat Enhanced Thematic Mapper+ (ETM+) sensor and ground measurements (LAI, NPP, GPP). The scaling approach for NPP and GPP was based on spatially-distributed application of a carbon cycle process model (Biome-BGC) over a 25 m grid covering the study area. An eddy covariance flux tower was maintained at each site and it provided meteorological data for input to Biome-BGC and estimates of GPP for comparison with BigFoot GPP. The BigFoot NPP and GPP products were aggregated spatially (i.e. averaging across 25 m cells) to match the 1-km resolution of the MODIS products. GPP was also aggregated temporally to 8-day averages to match the temporal resolution of the MODIS GPP products. Earlier BigFoot papers covered the BigFoot NPP/GPP protocols and site-specific BigFoot/MODIS comparisons (Turner et al., 2003a, 2005, in press). Results at the individual sites (Table 1) are available from the Oak Ridge National Laboratory Distributed Data Archive Center (ORNL, 2005). A file for each site contains the information and comparisons in Table 2.

2.2. MODIS NPP/GPP products

The MODIS NPP/GPP algorithm is described in Running et al. (2004) and Heinsch et al. (2003). A simple light use efficiency model (MOD17) is at the core of the GPP component of the algorithm and it requires daily inputs of incoming

Table 1
Location, vegetation type, climate descriptors, and related publication for the 9 BigFoot sites

Code	Vegetation	Location	Precipitation[a] (cm)	MAT[b] (°C)	Related publication
NOBS	Boreal forest	Lat: 55.885260 Lon: −98.477268	52	−3.2	Goulden et al., 1997
HARV	Hardwood forest	Lat: 42.528513 Lon: −72.172907	11	8.3	Wofsy et al., 1993
CHEQ	Mixed forest	Lat: 45.945404 Lon: −90.272475	75	5.3	Davis et al., 2003
METL	Conifer forest	Lat: 44.450722 Lon: −121.572812	4	7.7	Anthoni et al., 2002
TAPA	Tropical moist forest	Lat: −2.869745 Lon: −54.949355	159	26.4	Saleska et al., 2003
TUND	Arctic tundra	Lat: 71.271908 Lon: −156.613307	5	−10.9	Kwon et al., in press
SEVI	Desert grassland	Lat: 34.350858 Lon: −106.689897	3	13.6	Kurc and Small, 2004
KONZ	Tallgrass prairie	Lat: 39.089073 Lon: −96.571398	87	12.8	Ham and Knapp, 1998
AGRO	Corn/soybean	Lat: 40.006658 Lon: −88.291535	99	11.2	Meyers and Hollinger, 2004

[a] Annual precipitation (multiple year average).
[b] Mean annual temperature (multiple year average).

Table 2
Contents of site-specific BigFoot NPP/GPP summary files available at ORNL (2005)

1. BigFoot land cover map
2. BigFoot leaf area index (LAI) map
3. BigFoot LAI seasonal trajectory for dominant cover type
4. Tower meteorological data
5. BigFoot net primary production (NPP) map
6. Comparison of BigFoot and flux tower gross primary production (GPP)
7. Comparison (time series) of MODIS and BigFoot GPP
8. Comparison of MODIS and BigFoot NPP (bar graph)
9. Comparison of MODIS and BigFoot GPP (bar graph)
10. Comparison of DAO and flux tower meteorological data.
11. Comparison of MODIS and BigFoot FPAR
12. Comparison of MODIS and BigFoot LAI
13. Comparison of MODIS and BigFoot daily light use efficiency

photosynthetically active radiation (PAR), minimum temperature over the 24 h period, and daytime average vapor pressure deficit. These meteorological data are provided by the NASA Data Assimilation Office (DAO) based on a general circulation model that is continuously assimilating observations from space and ground stations. Additional MOD17 inputs include FPAR (multiplied by PAR to get absorbed PAR), and LAI (used to estimate biomass for the purposes of estimating R_a), which are both standard MODIS products.

Since MODIS was placed in orbit in 1999 there have been multiple updates or "Collections" of the MODIS land products. Here we use Collection 4.5 for the period 2000–2004, produced at the University of Montana. It reflects improvements over Collection 4 in the FPAR and climate inputs to MOD17 (Zhao et al., 2005). Collection 4.5 was also used in the validation study of Heinsch et al. (in press).

2.3. BigFoot NPP/GPP products

The approach to developing the BigFoot NPP and GPP products has been described previously (Turner et al., 2003a, 2005) and is briefly summarized here. Nine sites were chosen using the criteria that an eddy covariance flux tower is operating (required for meteorological data) and that the sites represent a wide range of biome types (Fig. 1). At each site, a 5×5 km study area was established in the vicinity of the flux tower. A set of 100 sample points was then selected. For 50 of the sample points, the distribution followed a cyclic sampling design in the 1 km^2 cell containing the flux tower (Berterretche et al., 2005; Burrows et al., 2002). The other 50 were distributed according to a stratified random design (AGRO, HARV, NOBS) or based on the criteria of sampling the spectral variation in the Landsat data. At all sample points, LAI was measured seasonally using the LAI-2000 or clipping (Campbell et al., 1999; Gower et al., 1999). At 50 of the sample points (a logistical constraint), aboveground NPP (ANPP) was measured using standard biome-specific approaches (Campbell et al., 1999; Gower et al., 1999). Belowground NPP was estimated based on the literature survey of Gower et al. (1999). The field measurements were made for a duration between one and three years depending on the site.

Biome-BGC (Kimball et al., 2000; Running & Hunt, 1993) was then applied in a spatially-distributed mode (i.e. cell-by-cell over a grid) at a 25 m resolution over the 25 km^2 study area. Model inputs included land cover type, daily LAI, and daily meteorological data (PAR, precipitation, minimum temperature, maximum temperature, and vapor pressure deficit). The land cover surfaces (Cohen et al., 2003a) and mid-growing season LAI surfaces were derived from Landsat ETM+ imagery (Cohen et al., 2003a,b, in press). Multiple images were acquired for each year that field measurements were made at a given site. The seasonal trajectory for the LAI was from observations of above and below canopy PAR (Wythers et al., 2003), downward looking radiometers, or repeated observations. The meteorological measurements were made at the flux towers (see references in Table 1).

The ecophysiological parameters for the Biome-BGC model were cover-type specific and generally from White et al. (2000). Two model parameters (foliar carbon to nitrogen ratio and fraction of foliar nitrogen as rubisco) were calibrated using the observed NPPs. Modeled GPP was compared to tower GPP over the area within 0.5 km radius of the flux tower (an approximation of the tower footprint). Tower GPP was estimated from half-hourly net ecosystem exchange (NEE)

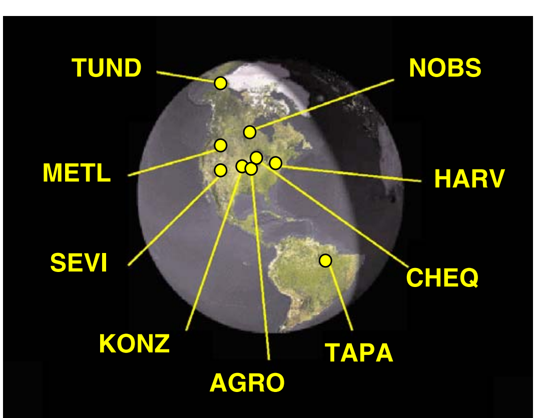

Fig. 1. Location of the 9 BigFoot sites. Site abbreviations are specified in Table 1.

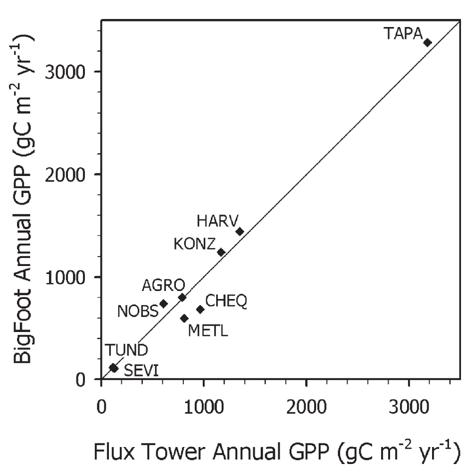

Fig. 2. Comparison of BigFoot and flux tower annual GPP at 9 sites. BigFoot values are means for all 25 m cells within a 0.5 km radius of the flux tower. Site abbreviations are listed in Table 1.

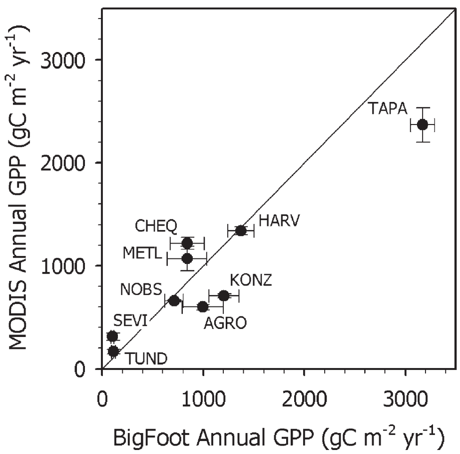

Fig. 3. Comparison of BigFoot and MODIS GPP estimates at 9 sites. Values are means for 25 1-km^2 MODIS cells +/− the standard deviations.

values (Goulden et al., 1996; Turner et al., 2003b) using Eq. (1) during daylight hours.

$$\mathrm{GPP} = \mathrm{NEE} - R_e \tag{1}$$

where R_e = ecosystem respiration. R_e is derived from the air or soil temperature and the relationship of nighttime NEE to air or soil temperature during periods of adequate turbulence.

2.4. MODIS/BigFoot comparisons

The BigFoot products were developed in the Universal Transverse Mercator (UTM) coordinate system and were reprojected to the native Sinusoidal Projection of the MODIS products for comparison (Cohen et al., 2003a). The BigFoot NPP/GPP data were then averaged over each 1 km^2 MODIS cell. These averages included zeros for nonvegetated grid cells. The BigFoot GPP data were also averaged over the 8 day bin periods associated with the MODIS GPP products. The year of comparison was site specific depending on when the BigFoot field measurements were made and flux tower meteorological observations were available (AGRO, KONZ, and CHEQ in 2000, TAPA in 2004, all others in 2002).

Besides the direct comparison of MODIS and ground-based NPP/GPP, several key components of the MODIS GPP algorithm were examined. The interpolated meteorological data from DAO were compared for the full 365 days with meteorological observations from the flux tower. FPAR values used in generating the MODIS NPP/GPP were compared with FPAR values derived from the BigFoot prescribed LAIs. The conversion of the prescribed LAIs to FPAR used a simple Beer's Law approach (Jarvis & Leverenz, 1983).

$$\mathrm{FPAR} = 1 - \left(e^{(\mathrm{LAI}^*(-K))}\right) \tag{2}$$

where K is the canopy light extinction coefficient (also an ecophysiological parameter in Biome-BGC). K values were assumed to be 0.58 for broadleaf forests and 0.50 for all other vegetation types (Jarvis & Leverenz, 1983). The ground-based FPAR values were averaged temporally to get 8-day mean values over each 1 km^2 that could be compared directly to the MODIS values.

Lastly, the daily light use efficiency (ε_g) values from MODIS and BigFoot were also compared. ε_g is a key variable in the MODIS GPP algorithm and is calculated at the quotient of GPP (in gC) and the PAR absorbed by the canopy (APAR in MJ). The MODIS daily ε_g was generated by running the MOD17 NPP/GPP algorithm (Running et al., 2000) at the tower cell with standard inputs from the MODIS data stream. For the BigFoot values, daily ε_g was calculated as modeled GPP divided by modeled APAR. All 25 m cells in the 1 km^2 MODIS cell that included the flux tower were spatially averaged for the comparison with MODIS ε_g.

3. Results

BigFoot annual GPP averaged over the 25 km^2 sites ranged from 115 to 3000 gC m^{-2} yr^{-1}. The site-specific comparison with GPP from the tower measurements showed generally good agreement (within 20%) across the sites except at CHEQ and METL (Fig. 2). At the CHEQ site, the tower GPP was derived from instrumentation at multiple heights above the ground (30, 122, 396 m), thus probably integrating over a much larger area than the 0.5 km radius footprint assumed in the BigFoot GPP (Davis et al., 2003). A large area of grassland at the base of the tower contributed to the low BigFoot GPP estimate. At METL, the BigFoot GPP did not show as strong of a decrease in GPP late in the growing season (probably associated with soil drought) as did the tower observations (Turner et al., 2005).

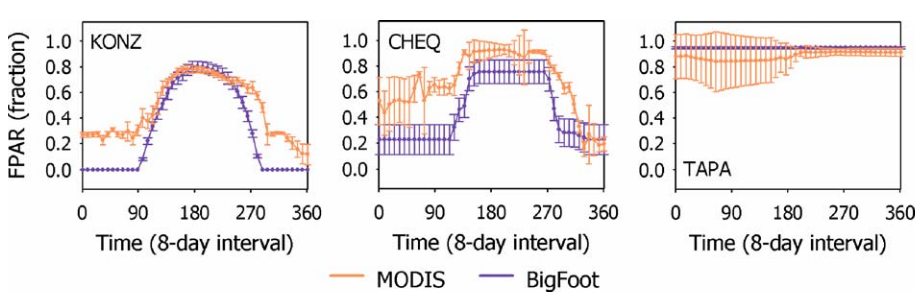

Fig. 4. Time series comparison of FPAR from BigFoot and MODIS at three sites (KONZ, CHEQ, TAPA). Values are means and standard deviations for 25 1-km^2 MODIS cells. Bins follow the 8-day temporal resolution of the MODIS FPAR product. See Turner et al. (2005) or ORNL (2005) for comparable figures at the other BigFoot sites.

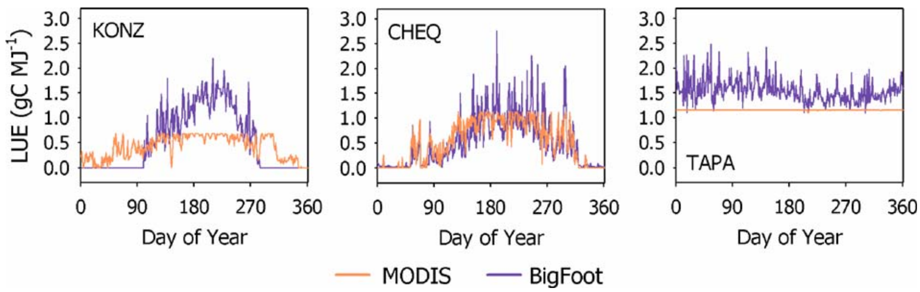

Fig. 5. Time series (daily) of light use efficiency for gross primary production (ε_g) for BigFoot and MODIS products at the MODIS cell occupied by the flux tower (KONZ, CHEQ, TAPA). See Turner et al. (2005) or ORNL (2005) for comparable figures at the other BigFoot sites.

The calibration procedure used in developing the BigFoot products reduced bias in mean NPP between measured and simulated values to less than 5% of the measured mean NPP for all combinations of cover type by site. The ratio of root mean square error (RMSE) to the mean of the measured NPPs ranged from 0.13 to 0.53 (mean ratio of 0.26) across all cover types and sites. The lowest RMSE to mean ratio was at the agricultural site, where productivity closely tracked LAI. The highest ratio was at the arctic tundra site (TUND) where mean NPP was very low.

The comparisons of annual GPP from BigFoot and MODIS (Fig. 3) showed close agreement at 2 forested sites, overestimation at 2 forested sites, and large underestimation at 1 forested site (TAPA). A principal driving factor in the overestimates was high FPAR relative to the BigFoot FPAR (e.g. CHEQ, Fig. 4). Relatively high FPARs also helped account for overestimations of GPP at two nonforest sites, TUND and SEVI. The KONZ and AGRO sites had large underpredictions of GPP, mostly related to a low value for the maximum light use efficiency parameter in the MODIS algorithm relative to the BigFoot estimates (e.g. KONZ, Fig. 5).

The comparison of MODIS and BigFoot NPP products had a similar pattern to that for GPP (Fig. 6). The ratio of NPP to GPP in the BigFoot products ranged from a low of 0.3 at NOBS to a high of 0.6 at TUND (Fig. 7), within the reported range of 0.25 to 0.65 in the literature (Amthor, 2000). The MODIS NPP:GPP ranged from 0.35 at HARV to 0.8 at SEVI and was overestimated as often as underestimated. The unusually high value at SEVI was primarily a function of overestimating GPP rather than underestimating R_a (Turner et al., 2005). NPP:GPPs for the two conifer-dominated sites were almost twice as high in the MODIS estimates compared to the BigFoot estimates and those differences contributed significantly to the overestimation of NPP by MODIS at those sites.

The spatial heterogeneity in the BigFoot GPP and NPP products was generally similar to or greater than that in the MODIS products (Figs. 3 and 6). Variability in the BigFoot products was even greater at the 25 m resolution because the Landsat data captured a wider array of vegetation types and more of the extremes in LAI. In the case of the agricultural site (AGRO), another contribution to the greater variability in the BigFoot products was that the large difference in light use efficiency between corn and soybeans was accounted for, something the MODIS product could not do because landcover was all classified as cropland (Cohen et al., 2003a; Turner et al., 2002). The one case where variability in the MODIS product was relatively high was at the tropical rain forest site (TAPA). That site was generally quite homogeneous, but problems with cloud effects on FPAR and LAI estimates introduced artificial variation into the MODIS products (Cohen et al., in press).

Of the three meteorological variables used in the MOD17 algorithm, PAR is most important because MOD17 is a light use efficiency model. Except for the most climatologically extreme

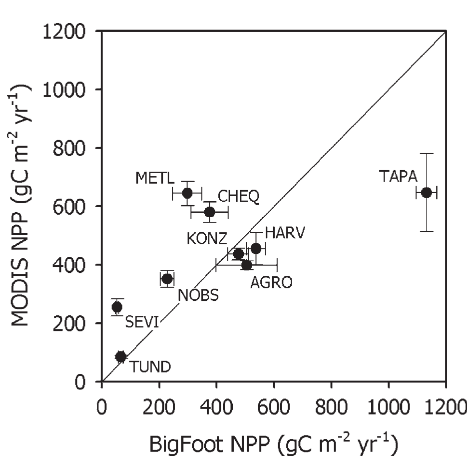

Fig. 6. Comparison of BigFoot and MODIS NPP estimates at 9 sites. Values are means and standard deviations for 25 1-km² MODIS cells.

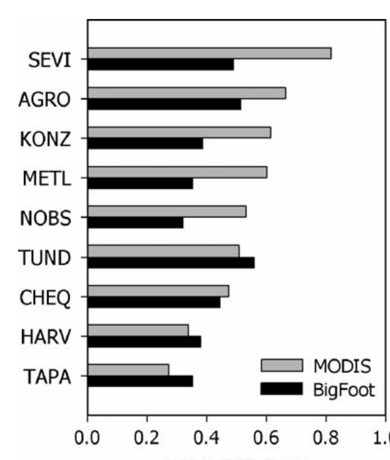

Fig. 7. Comparison of BigFoot and MODIS NPP to GPP ratio estimates at 9 sites. Values are for the 25 km² study area.

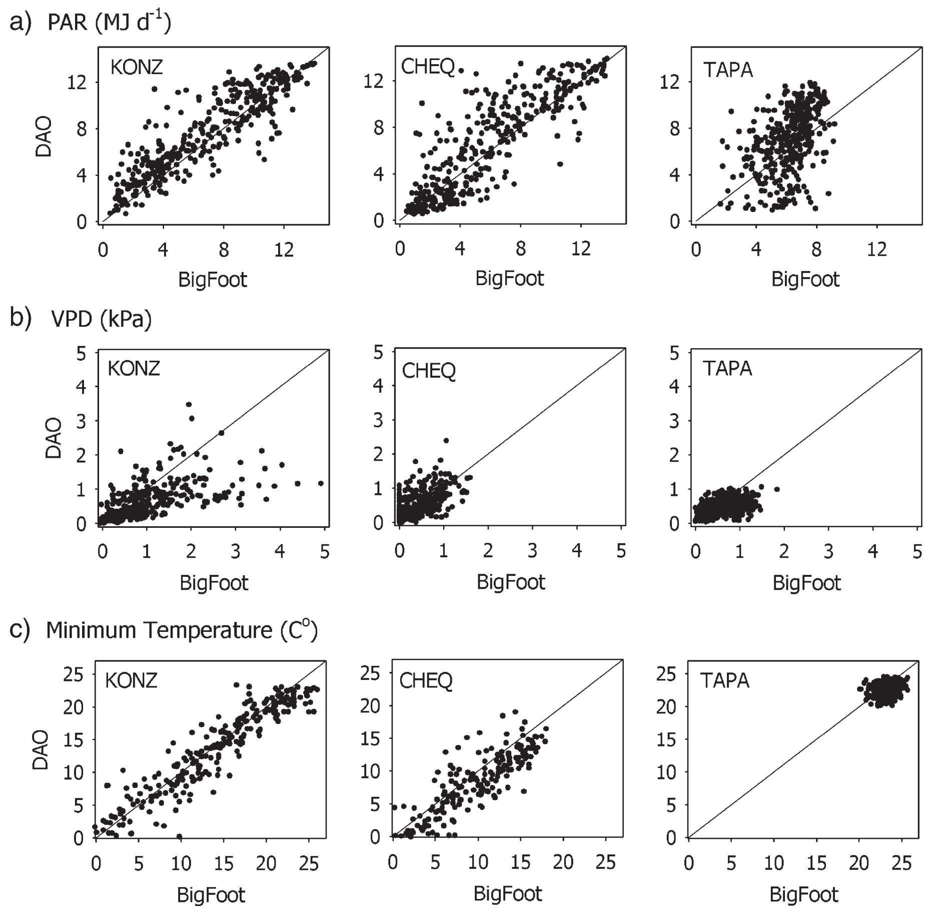

Fig. 8. Comparisons between flux tower and NASA Data Assimilation Office meteorological data for three sites (KONZ, CHEQ, TAPA). See Turner et al. (2005) or ORNL (2005) for comparable figures at the other BigFoot sites.

sites (TAPA and TUND), the DAO PAR was usually close to the observations (Fig. 8). At TUND, the DAO PAR estimates had a low bias at the high end of the PAR range, a period when plant growth is near its seasonal maximum rate. Note however, that getting PAR correct would have aggravated the GPP overestimation. At TAPA, there was little relationship between DAO and tower PAR estimates, probably because of problems with accounting for recurrent cloudiness in the DAO PAR estimates. The only consistent bias in the VPD comparison was at SEVI where the DAO VPD was consistently lower than the tower observations. At SEVI, higher VPDs would have decreased the MODIS GPP, bringing it into closer agreement with the ground measurements.

Maximum FPAR showed good agreement in most cases (Fig. 4). As noted, the apparent overestimates at SEVI, METL, and CHEQ contributed to the high MODIS GPP estimates at those sites. The MODIS FPAR trajectories usually showed strong seasonality, but there was increase in advance of the beginning of the growing season (HARV, TUND, AGRO) or delay of the end of the growing season (AGRO, KONZ, CHEQ) at some sites. These discrepancies did not contribute notably to explaining the differences between BigFoot and MODIS in annual NPP and GPP.

Lastly, the time series comparisons of LUE showed a general tendency for the MODIS algorithm to underestimate daily LUE (Fig. 5). This underestimation was most apparent at the AGRO site where BigFoot LUE and tower-based LUE were about 3 times the MODIS estimate (Turner et al., 2003b, 2005). A consistently greater day-to-day variation in the BigFoot LUE is also apparent across sites. The pattern occurs because LUE is independent of PAR in MOD17 whereas in the Biome-BGC model used in the BigFoot estimates has an asymptotic relationship of GPP to PAR, hence LUE is highest under overcast conditions and decreases under clear sky conditions.

4. Discussion

4.1. Cross-site patterns in NPP/GPP comparisons

The BigFoot approach to scaling NPP and GPP over a 25 km^2 area served to integrate site-level measurements of meteorological data, NPP, GPP, land cover, and LAI. Any discrepancy, as at METL where tower GPP was greater than BigFoot GPP, should be considered in the BigFoot/MODIS comparisons. At METL, the MODIS GPP was considerably higher than both BigFoot and tower GPP, so the conclusion that MODIS GPP was overestimated is probably still warranted. Such alternative validation approaches, i.e. simply checking MODIS GPP over 25 km^2 with tower GPP (Heinsch et al., in press) and checking MODIS NPP against plot level measurements made for the most part in years prior to the MODIS era (Zhao et al., 2005, 2006), are adequate for a first order evaluation of the MODIS products but are strongly complemented by the BigFoot approach at selected sites.

For both NPP and GPP, there was not an overall bias in the MODIS products: as many sites were underestimated relative to the BigFoot products as were overestimated. To some degree that helps explain why the global NPP estimate from MODIS (~55 Pg yr^{-1}, Running et al., 2004; Zhao et al., 2005) is close to the canonical 60 PgC yr^{-1} estimated from the areas of different biomes and their representative mean NPP values (Saugier et al., 2001).

There was a trend in the MODIS products towards overestimation of NPP and GPP at low productivity sites and underestimation at high productivity sites. A similar pattern is seen for GPP comparisons over 15 flux tower sites by Heinsch et al. (in press) and for NPP comparisons outside the tropical zone in Zhao et al. (2005). Specific problems with the DAO meteorological data and errors in land cover classification have been treated in Heinsch et al. (in press) and Zhao et al. (2005, 2006). Generally, however, the overestimation appears to be primarily a problem with high MODIS FPARs, both mid-growing season maxima and high values outside the growing season (see below). The underestimations are primarily a function of low values for the maximum light use efficiency (see below). In some cases (e.g. at HARV), there were counteracting errors such that high FPARs compensated for low LUE values resulting in close agreement of MODIS and BigFoot GPP on an annual basis (Turner et al., 2003a).

The cases of poor agreement between BigFoot and MODIS products with respect to NPP:GPP can be traced to differences in either GPP or R_a. At SEVI, the R_a estimates agreed, but as noted the SEVI GPP was too high because of high FPARs. For grasslands globally, the NPP/GPP was 0.65 (Zhao et al., 2005), so this may be a general phenomenon for that cover type. At the boreal forest site (NOBS), NPP:GPP was 0.6 relative to the BigFoot estimate of 0.3, and relative to a previous estimate of 0.25 for that site based on chamber measurements and scaling of R_a from biomass and temperature (Ryan et al., 1997). A possible explanation for the low R_a estimate from MOD17 is that the base rate of R_a (gC gC^{-1} h^{-1} at a reference temperature) is not adjusted upwards as a function of decreasing mean annual temperature as has been suggested by a variety of ecophysiological studies (e.g. Larigauderie & Korner, 1995). Ecosystem process models are increasingly incorporating simple temperature dependent algorithms for adjusting the base rate or Q_{10} values in their calculation of R_a (Wythers et al., 2005), an innovation that could be especially beneficial in global scale applications.

The MODIS R_a estimate is also strongly influenced by the MODIS LAI product. In MOD17, the MODIS LAI is converted to total plant biomass by reference to multiple allometric variables (Running et al., 2000). An underestimate of LAI at the KONZ site (Cohen et al., in press) resulted in a much lower MODIS R_a than the BigFoot R_a estimate and hence a much higher NPP:GPP. A more comprehensive analysis of MOD17 R_a would include evaluation of the allometric parameters relating LAI to biomass, something beyond the scope of this study.

4.2. FPAR inputs to MODIS GPP

The logic for including FPAR in the MODIS GPP algorithm relates to optimization theory, i.e. that vegetation will only display as much green biomass as can be efficiently exploited (Field et al., 1995). Rigorous validation of the MODIS FPAR product is difficult and has been made in only a few cases, primarily in ecosystems with low FPAR (Fenshlot et al., 2004; Myneni et al., 2002). The comparisons here are compromised to some degree because the BigFoot FPAR estimates were based on measurements and modeling of LAI and conversion to FPAR using Beer's Law, thus not accounting for details of canopy structure and solar geometry. Nevertheless some general observations may be warranted.

For the purposes of the MODIS GPP algorithm, one of the most critical points of information derived from the MODIS FPAR can be the beginning of the growing season. At the end of the growing season, falling levels of PAR and low temperatures provide a strong signal for lower GPP that is independent of FPAR. Both Xiao et al. (2004) and Turner et al. (2005) noted that the MODIS GPP anticipated the actual rise in GPP in spring at the HARV site, an effect driven primarily by MODIS FPAR. A similar anticipation of the growing season was noted by the MODIS LAI product at a beech forest site (Wang et al., 2005). The MODIS FPAR and LAI are maximum value composites over 8 day windows which would tend to shift the spring greening earlier, however the magnitude of this effect would not be large. Also, there may be greening of understory herbs in temperature deciduous forests that would influence the MODIS FPAR but one would expect GPP to start showing up in the tower measurements if much green biomass had accumulated.

MODIS GPP also began its spring rise too early at the TUND site. Measurements with a downward looking radiometer suggest that the MODIS FPAR at TUND is probably capturing snow melt-off (Stow et al., 2004), but there is apparently a delay in photosynthesis until soil thaw has progressed to some degree (Van Wijk et al., 2003). The MODIS GPP algorithm uses a simple minimum temperature scalar (Running et al. 2000; Turner et al., in press) and it may require calibration or supplemental information about soil temperature to capture spring startup of photosynthesis at high latitude sites.

At the BigFoot grassland/cropland sites (KONZ, SEVI and AGRO) there was a spring rise in FPAR that correlated with the observations, but there was a problem with FPARs outside the growing season. Values of 0.3 or more were maintained throughout the year which tended to generate significant GPP outside the growing season. Significant MODIS FPAR outside the growing season was also seen at a semi-arid grassland site in Africa (Fenshlot et al., 2004). It's not clear if this is an issue with screening for effects of winter snow and clouds or possibly problems with soil reflectance.

In general, the maximum growing season FPAR from MODIS was close to the observations. The notable exceptions were at the open conifer site (METL) and the desert grassland site (SEVI). These were also the only sites with a significant proportion of bare ground, which may have complicated the radiation transfer modeling. MODIS FPAR was also found to be overestimated in two other relatively low FPAR sites (Fenshlot et al., 2004; Huermmrich et al., 2005).

4.3. LUE inputs to MODIS GPP

Studies at eddy covariance flux tower sites have revealed clear differences between biome types in light use efficiency for GPP at the daily time step (Turner et al., 2003b). Studies at large spatial scales using satellite-based APAR and ground-based statistics on productivity also indicate cover type differences in LUE (Lobell et al., 2002). These findings support the general approach in MOD17 of specifying maximum light use efficiency ($e_{g\text{-max}}$) for each biome. The original parameterization of $e_{g\text{-max}}$ in MOD17 was based on an analysis of modeled global terrestrial GPP (Running et al., 2000), and it may be desirable to adjust parameter values as e_g is measured at an increasing number of flux tower sites.

Across the nine BigFoot sites, the MODIS $e_{g\text{-max}}$ appears to be underestimated in all cases except METL. The most extreme case is at AGRO where the actual e_g is relatively high because of artificially selected and fertilized crops (Gower et al., 1999; Suyker et al., 2005). However, even the grassland $e_{g\text{-max}}$ is low relative to the observations at KONZ (Turner et al., 2003b). There is possibly a high bias in the tower GPP estimates (hence a high e_g) if foliar dark respiration is suppressed during the day as some have suggested (Wohlfahrt et al., 2005). However, the magnitude of this effect would be small relative to the differences in e_g seen here.

A related issue is that e_g in MOD17 does not respond to overcast conditions. Observations at flux towers suggest that there can be saturation of canopy photosynthesis on clear sky days even at the daily time step (Turner et al., 2003b). Hence, light use efficiency is highest on overcast days and decreases on clear sky days. The current $e_{g\text{-max}}$ values used in MOD17 appear to be maxima that would be expected under clear sky conditions. An alternative formulation of the GPP algorithm could be envisioned that specified a different $e_{g\text{-max}}$ under clear sky and overcast conditions, then ranged between those values depending on the degree of cloudiness.

Although it is not regulated by PAR, $e_{g\text{-max}}$ is adjusted downward for unfavorable conditions indicated by extremes of minimum temperature (T_{min}) or VPD (Running et al., 2000). The T_{min} scalar (0–1) is particularly important at high latitudes and was shown to have helped MOD17 capture interannual variation in GPP at the NOBS site (Turner et al., in press). Note, however, that a comparison of tower GPP and MODIS GPP at a different boreal forest site indicated a possible oversensitivity in MOD17 to decreasing temperature late in the growing season (Martel et al., 2005). The VPD scalar was effective at reducing GPP during a dry period at the SEVI site (Turner et al., 2005) but appeared to be oversensitive at the HARV site (Turner et al., 2003a). Leuning et al. (2005) examined the possible benefits of adding a simple water balance scalar to MOD17 and found it helped appreciably in a savannah ecosystem. These observations suggest that the biome-specific parameters that control sensitivity to T_{min} and VPD should be examined at multiple sites within each biome.

A very general issue with $e_{g\text{-max}}$ is that it sometimes varies significantly over relatively short distances in association with spatial heterogeneity of the vegetation. The clearest case is at the AGRO site where the heterogeneity is associated with a mix of fields growing corn or soybeans (Turner et al., 2002). A given 1-km^2 grid cell at AGRO is usually a mixture of crop types (Cohen et al., 2003a), but the light use efficiency of corn is significantly higher than that of soybean (Suyker et al., 2005). At the NOBS site, the black spruce and muskeg (or open black spruce) cover types occur in close proximity over the landscape. However, field measurements suggest that light use efficiency is higher for the black spruce cover type, most likely because of better drained soils (O'Connell et al., 2003). At the TUND site, ice wedge polygons create fine scale heterogeneity in microtopography (at the scale of meters) which is associated with differences in NPP (Stow et al., 2004). Thus, the scale dependence in NPP estimation is an issue in many of the biomes. Approaches to accommodating this heterogeneity in the coarse resolution analyses often include carrying over information on land cover from finer scale remote sensing (Chen, 1999; Turner et al., 2002).

4.4. Continued NPP/GPP validation efforts

As this study and that of Heinsch et al. (in press) have shown, eddy covariance flux tower sites are well suited for validation of the MODIS GPP product. The flux tower community is organized globally under the auspices of FLUXNET (Baldocchi et al., 2001) and regional networks such as AmeriFlux. Standardized datasets for GPP at the network sites are increasingly available (Falge et al., 2002; Law et al., 2002). The fact that a flux tower footprint usually integrates GPP over mixtures of cover types helps obviate the problem with fine scale heterogeneity in light use efficiency noted earlier, and provides a strong rationale for parameterizing $e_{g\text{-max}}$ based on flux tower observations.

It would not be difficult to do a standardized optimization of the five key parameters in the MOD17 GPP algorithm using tower GPP data (e.g. Leuning et al., 2005). Comparisons of these optimized parameters across different sites within a biome would then be informative with respect to assessing uncertainty in the MODIS GPP product.

Validation of NPP does not depend on flux tower measurements. However, adding NPP to a standard set of site-level measurements at flux towers would be very beneficial for the purposes of MODIS NPP validation. The issues with scaling NPP over a large enough area to perform comparisons with MODIS products could be addressed using an approach along the lines of the BigFoot protocol. NPP measurements are valuable in their own right at the tower sites because they help partition ecosystem carbon flux into its components of GPP, R_a, and heterotrophic respiration (Law et al., 2000). A better understanding of the ratio of NPP to GPP at tower sites would lead to new insights on general patterns in NPP:GPP and progress in modeling NPP.

NPP is probably measured at a wider range of sites globally than is the case for GPP and it is desirable that these measurements be brought to bear on validating the MODIS NPP product (Turner et al., 2004). The Global Terrestrial Observing System (GTOS) has identified NPP an early test case parameter for global monitoring and is supporting the compilation of global NPP data (GTOS, 2005). A significant impetus towards organizing a global set of sites for MODIS NPP/GPP validation has also been provided by the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC). The DAAC web site (DAAC, 2005) provides a complete suite of MODIS products including reflections, spectral vegetation indices, and NPP/GPP for 7×7 km areas at 26 sites globally (Running et al., 2004). The intent is that these data be downloaded and used by site-level researchers in application and testing of NPP models.

Ultimately, it will be desirable to go beyond a limited sample of validation sites and test the NPP/GPP products at the regional to global scale (Running et al., 1999). Inverse modeling based on the spatial and temporal patterns in atmospheric CO_2 concentration can provide independent regional and global estimates of net ecosystem production (the net effect of NPP and heterotrophic respiration). If the MODIS NPP/GPP algorithm is coupled to an R_h algorithm, then MODIS based NEP could be compared with NEP estimated from inverse modeling.

5. Conclusions

The global GPP and NPP products from the MODIS sensor provide a new means to monitor the terrestrial biosphere. Validation efforts are required to establish the effectiveness of the NPP/GPP algorithm, but significant scaling issues must be addressed to accomplish a clear juxtaposition of the MODIS products and ground-based measurements. The BigFoot Project developed a protocol for addressing many of these scaling issues and implemented that protocol at 9 sites covering a wide range of biome types. Results suggest that the MODIS NPP and GPP products are responsive to general trends in the magnitude of NPP and GPP associated with local climate and land use, but tend to be overestimated at low productivity sites and underestimated at high productivity sites. Analysis of the meteorological data inputs, FPAR inputs, and the parameterization of light use efficiency in MOD17 can provide insights into the site-specific causes of differences between MODIS and BigFoot products. Measurements of NPP and FPAR are needed at a wider range of sites, particularly at eddy covariance flux tower sites, to achieve a more comprehensive evaluation of the MODIS NPP/GPP products.

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